3-Phase BLDC Drive Using Variable DC Link Six-Step Inverter

Designer Reference Manual

56800E
16-bit Digital Signal Controllers

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3-Phase BLDC Drive Using DC/DC Inverter

Designer Reference Manual

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The following revision history table summarizes changes contained in this document. For your convenience, the page number designators have been linked to the appropriate location.

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May, 2006	1	Changed hybrid controller to digital signal controller Changed DC/DC inverter to variable DC link six-step inverter Minor edits to clarify Chapter 1 Renamed Section 2.4 to better reflect contents and added information at end of section	Various Various 7 17

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Chapter 1
Introduction

1.1 Introduction

This paper describes the design of a 3-phase BLDC drive using a variable DC link six-step inverter, based on Freescale's MC56F8013 dedicated motor control device.

Recently, small high-speed BLDC motors have become very popular in a wide application area. The BLDC motor does not have a mechanical commutator and is, consequently, more reliable than the DC motor. Small high-speed BLDC motors have very low inductance compared to conventional BLDC motors. When PWM control is applied to the phases of a BLDC motor, the current follows the rectangular PWM voltage shape. This rapidly changing current magnetizes and demagnetizes the motor iron at a frequency equal to the PWM frequency. Due to magnetic hysteresis losses, the motor can become hot enough to be damaged and the high current ripple will cause other losses. Because of the special control required by the motor, the method adopted in this reference design uses a variable DC link six-step inverter r to generate the desired voltage for the motor. The motor then requires only a conventional three-phase inverter for commutation.

The concept of the application is a high-speed BLDC motor with closed-loop speed-control. It serves as a design example of a 3-phase BLDC drive with variable DC link six-step inverter, using a Freescale digital signal controller.

This reference design includes basic motor theory, system design concept, hardware implementation, and the software design, including the FreeMASTER software visualization tool.

1.2 Freescale Controller Advantages and Features

The Freescale MC56F801x family is well suited to digital motor control, combining the DSP's calculation capability with the MCU's controller features on a single chip. These digital signal controllers offer many dedicated peripherals such as pulse width modulation (PWM) modules, analog-to-digital converters (ADC), timers, communication peripherals (SCI, SPI, I^2C), and on-board Flash and RAM.

The MC56F801x family members provide the following peripheral blocks:

- One PWM module (although with a limited pinout on the MC56F8014) with PWM outputs, fault inputs, fault-tolerant design with dead time insertion, supporting both center-aligned and edge-aligned modes
- 12-bit ADCs, supporting two simultaneous conversions; ADC and PWM modules can be synchronized
- One dedicated 16-bit general purpose quad timer module
- One serial peripheral interface (SPI)
- One serial communications interface (SCI) with LIN slave functionality
- One inter-integrated circuit (I^2C) port
- On-board 3.3V to 2.5V voltage regulator for powering internal logic and memories

- Integrated power-on reset and low voltage interrupt module
- All pins multiplexed with general purpose input/output (GPIO) pins
- Computer operating properly (COP) watchdog timer
- External reset input pin for hardware reset
- JTAG/On-Chip Emulation (OnCE™) module for unobtrusive, processor-speed-independent debugging
- Phase-locked loop (PLL) based frequency synthesizer for the digital signal controller core clock, with on-chip relaxation oscillator

Table 1-1. Memory Configuration

Memory Type	MC56F8013	MC56F8014
Program Flash	16 Kbyte	16 Kbyte
Unified Data/Program RAM	4 Kbyte	4 Kbyte

BLDC motor control benefits greatly from the flexible PWM module, fast ADC, and quad timer module.

The PWM offers flexibility in its configuration, enabling efficient control of the BLDC motor. The PWM block has the following features:

- Three complementary PWM signal pairs, six independent PWM signals (or a combination)
- Complementary channel operation features
- Independent top and bottom dead time insertion (56F8013)
- Separate top and bottom pulse width correction via current status inputs or software
- Separate top and bottom polarity control
- Edge-aligned or center-aligned PWM reference signals
- 15-bit resolution
- Half-cycle reload capability
- Integral reload rates from one to sixteen periods
- Mask/swap capability
- Individual, software-controlled PWM output
- Programmable fault protection
- Polarity control
- 10mA or 16mA current sink capability on PWM pins
- Write-protectable registers

The PWM module is capable of controlling two PWM signals for the variable DC link six-step inverter. It can be configured to a switching frequency of 100kHz with a resolution of 1 in 960, i.e. almost 10-bit. The PWM module generates its reload signal; it can then be used to synchronize other modules to the PWM.

The four remaining PWM channels are used for phase A and phase B of the 3-phase inverter, which takes care of the motor commutation using the mask feature of the DSC. Phase C is controlled by two GPIO pins.

The ADC module has the following features:

- 12-bit resolution
- Dual ADCs per module; three input channels per ADC
- Maximum ADC clock frequency of 5.33MHz with a 187ns period
- Sampling rate of up to 1.78 million samples per second
- Single conversion time of 8.5 ADC clock cycles (8.5 x 187ns = 1.59ms)
- Additional conversion time of six ADC clock cycles (6 x 187ns = 1.125ms)
- Eight conversions in 26.5 ADC clock cycles (26.5 x 187ns = 4.97ms) using parallel mode
- Ability to use the SYNC input signal to synchronize with the PWM (provided the integration allows the PWM to trigger a timer channel connected to the SYNC input)
- Ability to sequentially scan and store up to eight measurements
- Ability to scan and store up to four measurements on each of two ADCs operating simultaneously and in parallel
- Ability to scan and store up to four measurements on each of two ADCs operating asynchronously to each other in parallel
- Interrupt generating capabilities at the end of a scan when out-of-range limit is exceeded and on zero crossing
- Optional sample correction by subtracting a pre-programmed offset value
- Signed or unsigned result
- Single-ended or differential inputs
- PWM outputs with hysteresis for three of the analog inputs

The ADC is used to measure DC bus voltage, variable DC link six-step inverter output voltage, DC bus current, and +0.2V voltage and +1.65V current references.

The application uses the ADC block in simultaneous mode scan. It is synchronized to the PWM pulses. This configuration allows the simultaneous conversion of the required analog values of current and voltage within the required time.

The quad timer is an extremely flexible module, providing all required services relating to time events. It has the following features:

- Four 16-bit counters/timers
- Count up/down
- Counters are cascadable
- Programmable count modulus
- Maximum count rate equal to the peripheral clock/2, when counting external events
- Maximum count rate equal to the peripheral clock/1, when using internal clocks
- Count once or repeatedly
- Counters are preloadable
- Counters can share available input pins
- Each counter has a separate prescaler
- Each counter has capture and compare capability

The application uses four channels of the quad timer for:

- PWM-to-ADC synchronization
- Hall sensor edge scanning used for speed calculation
- System base for ramp and speed control
- Commutation advance control

Chapter 2
Control Theory

2.1 BLDC Motor

A brushless DC (BLDC) motor is a rotating electric machine where the stator is a classic 3-phase stator, like that of an induction motor, and the rotor has surface-mounted permanent magnets (see Figure 2-1).

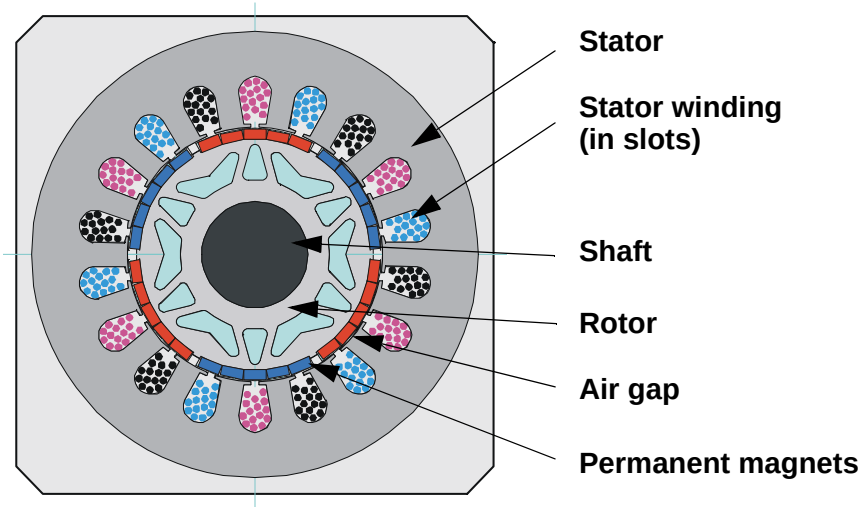
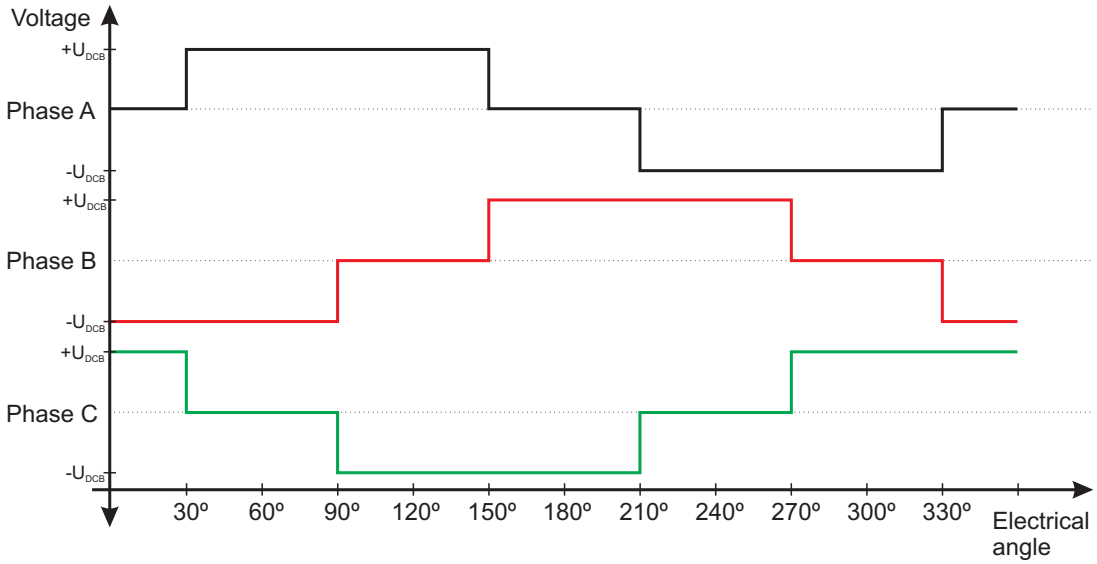


Figure 2-1. BLDC Motor — Cross Section

In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which the magnet rotates while the conductors remain stationary. In the DC commutator motor, the current polarity is altered by the commutator and brushes. On the contrary, in the brushless DC motor, the polarity reversal is performed by power transistors switching in synchronization with the rotor position. Therefore, BLDC motors often incorporate either internal or external position sensors to discern the actual rotor position; alternatively, the position can be detected without sensors.

2.2 BLDC Motor Control Using a Variable DC Link Six-Step Inverter

The BLDC motor is driven by rectangular voltage waveforms coupled with the given rotor position (see Figure 2-2). The generated stator flux interacts with the rotor flux generated by a rotor magnet, defining the torque, and thus speed, of the motor. The voltage waveforms must be properly applied to the two phases of the 3-phase winding system, to keep the angle between the stator flux and the rotor flux close to 90° to generate maximum torque. To achieve this, the motor requires electronic control for proper operation.



3-phase

Figure 2-2. Voltage Waveforms Applied To the 3-phase BLDC Motor

For standard BLDC motors, a power stage with a 3-phase inverter is used. Control is provided by applying PWM waveforms to the MOSFETs of the 3-phase inverter. However, there are small high-speed BLDC motors with very low inductance. If PWM is applied to the MOSFETs of the 3-phase inverter of such a motor, the current waveform will copy the PWM voltage waveform. Such a current waveform will rapidly and frequently magnetize and demagnetize the metal causing huge thermal losses due to magnetic hysteresis. Therefore, these BLDC motors require a special power stage with a variable DC link six-step inverter, illustrated in Figure 2-3. The power stage uses six power transistors fully turned on/off to control the commutation. The voltage level is controlled by two transistors in the variable DC link six-step inverter.

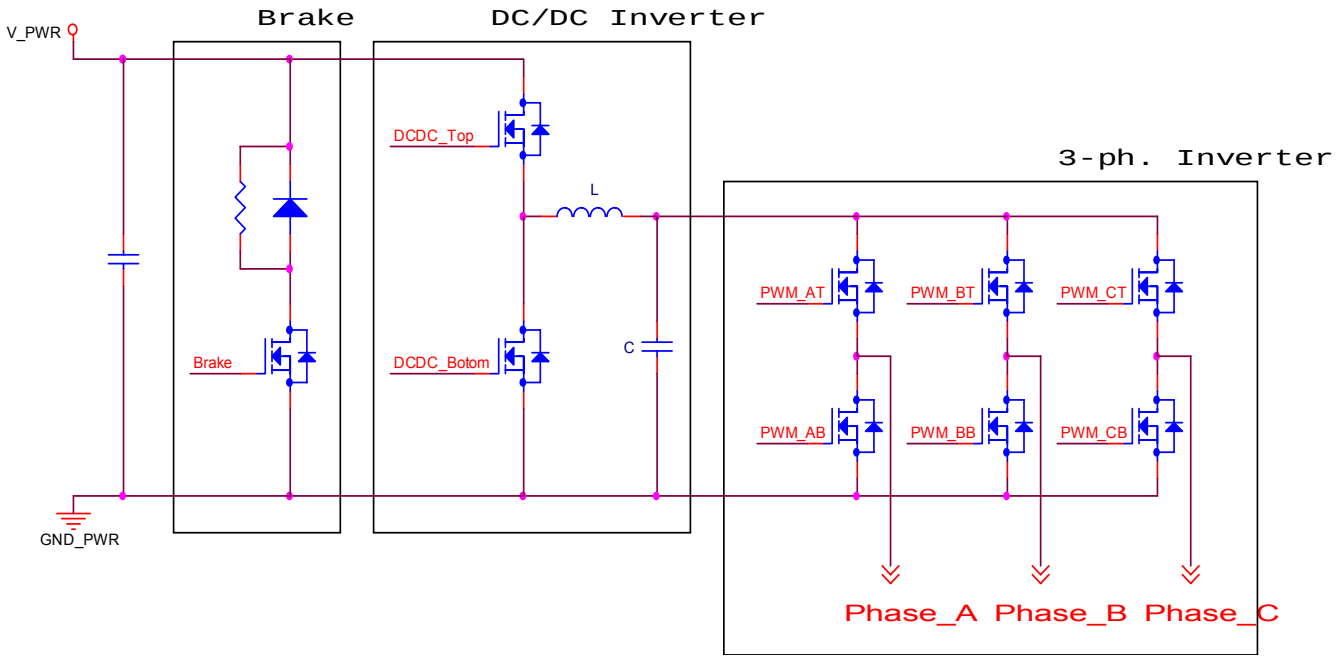


Figure 2-3. 3-Phase BLDC Power Stage with a Variable DC Link Six-Step Inverter

The variable DC link six-step inverter controls the voltage on the motor, while commutation is performed by the 3-phase inverter. The variable DC link six-step inverter output is controlled by switching the DCDC_Top MOSFET (Figure 2-3). Thus, the variable DC link six-step inverter uses the inductor L and the capacitor C to keep output voltage at the desired level.

This variable DC link six-step inverter can also work in the opposite direction, i.e. during braking, it can transfer energy to the power supply's input voltage level. To reduce the load voltage level during motor braking, the DCDC_Bottom MOSFET is used. If this MOSFET is turned on, the inductor is charged. In the instant when the MOSFET is turned off, the energy accumulated in the inductor is transferred to the variable DC link six-step inverter's input. This temporarily causes a higher voltage at the input. For longer operations, the input capacitor will not absorb all the energy, and the input voltage will be higher. In this case, care must be taken, and the braking MOSFET must be turned on while the voltage is higher, to reduce the voltage to a safe level.

The bottom MOSFET of the variable DC link six-step inverter operates in a different way to the top one, i.e. whereas the top MOSFET can be switched from 0 to 100% of the duty cycle, the bottom one cannot. The bottom MOSFET can only be switched from 0 to a certain percentage, because the inductor is discharged when the MOSFET is turned off. This maximum duty cycle depends on the voltages at both the input and the output.

The 3-phase inverter energizes two BLDC motor phases at the same time. The third phase is not powered (see Figure 2-2). Thus, we have six voltage vectors that may be applied to the BLDC motor.

2.3 Commutation

Commutation provides the creation of a rotation field. As explained previously, for proper operation of a BLDC motor it is necessary to keep the angle between the stator and rotor flux close to 90°. With six-step control we get a total of six possible stator flux vectors. The stator flux vector must be changed at a certain rotor position. The rotor position is usually sensed by Hall sensors. The Hall sensors generate three signals also comprising six states. Each of the Hall sensor states corresponds to a certain stator flux vector. All Hall sensor states with corresponding stator flux vectors are illustrated in Figure 2-4. The same figure is illustrated in tables Table 2-1 and Table 2-2.

The next two figures depict the commutation process. The actual rotor position in Figure 2-5 corresponds to the Hall sensors' state ABC[110] (see Figure 2-4). The actual voltage pattern can be derived from the Table 2-1. Phase A is connected to the positive DC bus voltage by the transistor PWM_AT, phase C is connected to ground by transistor PWM_CB, and phase B is not powered.

As soon as the rotor reaches a certain position (see Figure 2-5), the Hall sensor state changes its value from ABC[110] to ABC[100]. From Table 2-1 a new voltage pattern is selected and applied to the BLDC motor.

As can be seen, with a six-step control technique there is no possibility of keeping the angle between the rotor flux and the stator flux precisely at 90°. The real angle varies from 60° to 120°.

The commutation is repeated for each 60 electrical degrees. The angular (time) accuracy of the commutation event is critical; any deviation causes torque ripples leading to variations in speed.

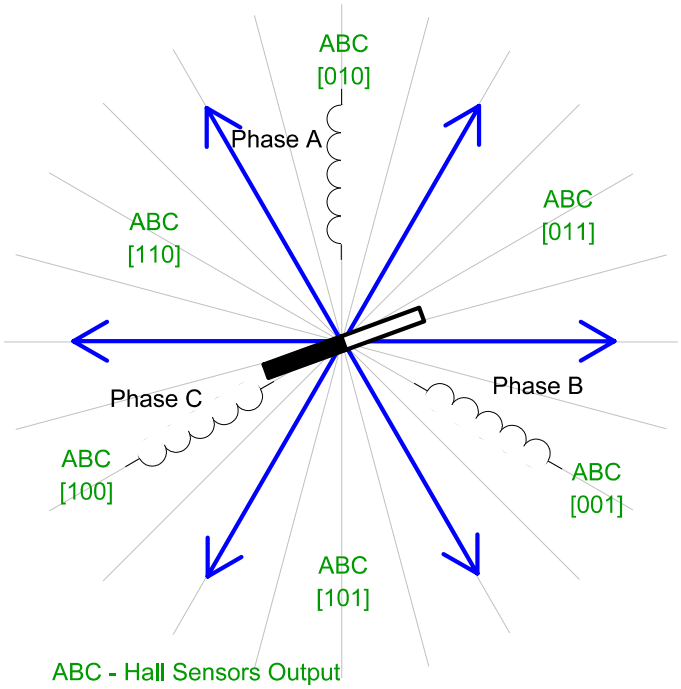


Figure 2-4. Stator Flux Vectors with Six-Step Control

Table 2-1. Commutation Sequence for Clockwise Rotation

Hall Sensor A	Hall Sensor B	Hall Sensor C	Phase A	Phase B	Phase C
1	0	0	$-V_{DCB}$	$+V_{DCB}$	NC
1	0	1	NC	$+V_{DCB}$	$-V_{DCB}$
0	0	1	$+V_{DCB}$	NC	$-V_{DCB}$
0	1	1	$+V_{DCB}$	$-V_{DCB}$	NC
0	1	0	NC	$-V_{DCB}$	$+V_{DCB}$
1	1	0	$-V_{DCB}$	NC	$+V_{DCB}$

Table 2-2. Commutation Sequence for Counterclockwise Rotation

Hall Sensor A	Hall Sensor B	Hall Sensor C	Phase A	Phase B	Phase C
1	0	0	$+V_{DCB}$	$-V_{DCB}$	NC
1	1	0	$+V_{DCB}$	NC	$-V_{DCB}$
0	1	0	NC	$+V_{DCB}$	$-V_{DCB}$
0	1	1	$-V_{DCB}$	$+V_{DCB}$	NC
0	0	1	$-V_{DCB}$	NC	$+V_{DCB}$
1	0	1	NC	$-V_{DCB}$	$+V_{DCB}$

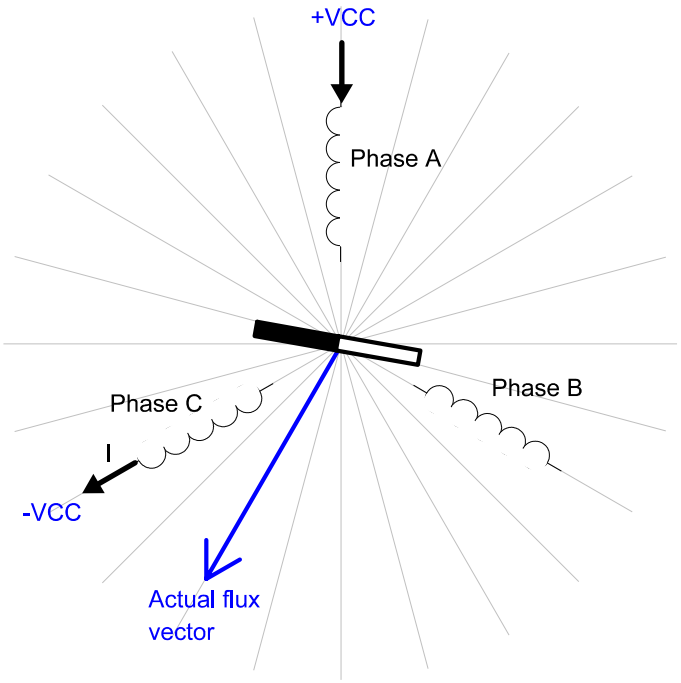


Figure 2-5. Situation Right Before Commutation

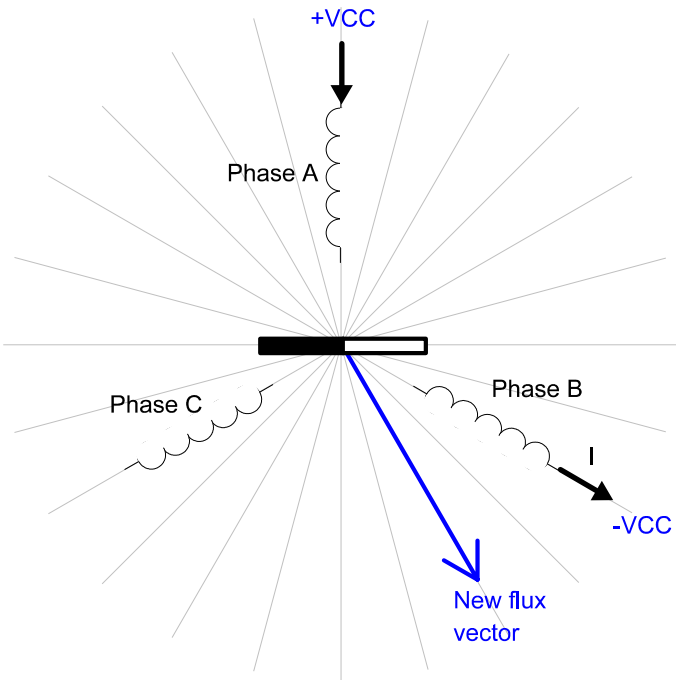


Figure 2-6. Situation Right After Commutation

2.4 Speed and Voltage Control

Commutation ensures proper rotor rotation of the BLDC motor, while the motor speed depends only on the amplitude of the applied voltage. The amplitude of the applied voltage is adjusted by the variable DC link six-step inverter using pulse width modulation. The required speed is controlled by a speed controller. The speed and voltage controllers are implemented as conventional PI controllers. The difference between the actual and required speed (voltage) is the input to the PI controller. Using this difference, the PI controller controls the duty cycle of PWM pulses fed to the variable DC link six-step inverter, corresponding to the voltage amplitude required to keep the desired speed. See Figure 2-7.

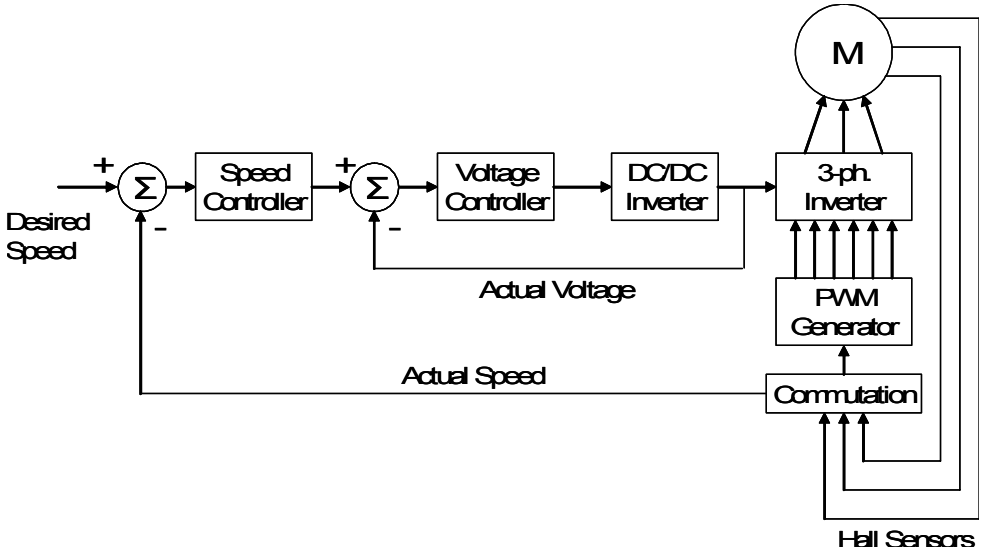


Figure 2-7. Speed Control

The speed controller calculates output voltage u(t) using a proportional-integral (PI) algorithm, in accordance with the following equations:

$$u(t) = K_c\left[e(t) + \frac{1}{T_I}\int_0^t e(\tau)d\tau\right] \quad (2\text{-}1)$$

After transformation to a discrete time domain using an integral approximation by a Backward Euler method, we get the following equations for the numerical PI controller calculation:

$$u(k) = u_P(k) + u_I(k) \quad (2\text{-}2)$$

$$u_P(k) = K_c \cdot e(k) \quad (2\text{-}3)$$

$$u_I(k) = u_I(k-1) + K_c\frac{T}{T_I} \cdot e(k) \quad (2\text{-}4)$$

where:

e(t)	=	Input error in time t	$u_p(k)$	=	Proportional output portion in step k
e(k)	=	Input error in step k	$u_I(k)$	=	Integral output portion in step k
w(k)	=	Desired value in step k	$u_I(k-1)$	=	Integral output portion in step k-1
m(k)	=	Measured value in step k	T_I	=	Integral time constant
u(t)	=	Controller output in time t	T	=	Sampling time
u(k)	=	Controller output in step k	K_c	=	Controller gain

The voltage controller calculates the output PWM duty cycle for the variable DC link six-step inverter using the same proportional-integral (PI) algorithm as the speed controller.

Chapter 3
System Concept

3.1 System Specification

The system is designed to drive a 3-phase BLDC motor. The application meets the following performance specification:

- Voltage control of BLDC motor using Hall sensors
- Targeted at the MC56F8013 controller board
- Running on 3-Phase Power Stage with DC/DC Inverter Lite
- Control technique incorporating:
  - Voltage BLDC motor control using variable DC link six-step inverter with voltage closed loop
  - Closed-loop BLDC motor speed control
  - Both directions of rotation (however, because an impeller is used in the application, the FreeMASTER page is locked to one direction only)
  - Both motor and generator modes
  - Starting from any motor position without rotor alignment
  - Minimum speed – 300 RPM
  - Maximum speed – 38000 RPM
- FreeMASTER software control interface (motor start/stop, speed setup)
- FreeMASTER software monitor
  - FreeMASTER software graphical control page (required speed, actual motor speed, start/stop status, DC bus voltage level, motor current, system status)
  - FreeMASTER software speed scope (observes actual and desired speeds)
  - FreeMASTER software Hall sensor scope (observes actual Hall sensors' state)
- DC bus overvoltage and undervoltage, overcurrent, Hall sensors cable fault protection

3.2 Application Description

A standard system concept is chosen for the drive (see Figure 3-1). The system incorporates the following hardware boards:

- Power supply 24V DC, 5A
- 3-Phase Power Stage with DC/DC Inverter Lite
- BLDC motor with Hall sensors
- MC56F8013 controller board

The 3-Phase Power Stage with DC/DC Inverter Lite runs the main control algorithm. In response to the user interface and feedback signals, it generates PWM signals for the variable DC link six-step inverter and 3-phase output signals for a 3-phase inverter.

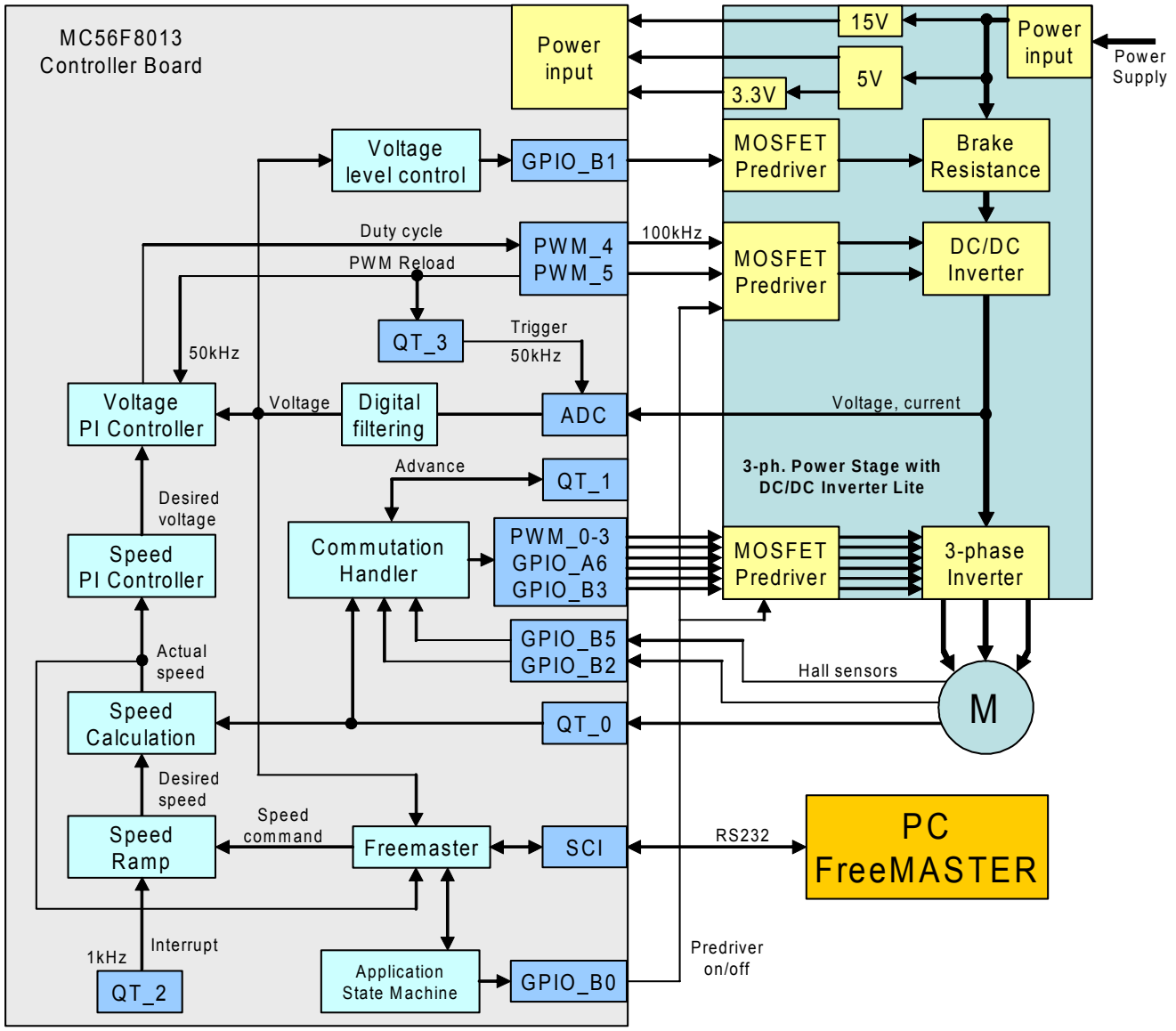


Figure 3-1. System Concept

3.3 Control Process

The state of the user interface is scanned periodically, while the speed of the motor is measured on each new arriving edge from the Hall sensors (only one phase is used for speed measurement). The speed command is calculated, according to the state of the control signals (Start/Stop, Speed from FreeMASTER). Then the speed command is processed by means of the speed ramp algorithm. The comparison between the actual speed command obtained from the ramp algorithm output and the measured speed generates a speed error. The speed error is input to the speed PI controller, generating a new desired voltage level for the voltage PI controller. The ADC is used to measure voltage at the variable DC link six-step inverter output and a digital filter is applied to this value. Then the filtered voltage is fed to the voltage PI controller. The comparison between the measured and desired voltages generates a voltage error. The voltage error is input to the voltage PI controller, generating a new duty cycle for the

variable DC link six-step inverter. The duty cycle value creates the PWM output for the variable DC link six-step inverter, and the commutation algorithm creates the output signals for the 3-phase inverter.

The Hall sensor signals are scanned independently of the speed control. Each new arriving edge of any Hall sensor signal calls the interrupt routine, providing the commutation algorithm. From a certain speed level the routine determines if the incoming Hall sensor edge is correct, by comparing it with a predicted signal.

As there is a delay between the Hall sensor edge and current commutation, the current is not symmetrical. To keep the current symmetrical, a so-called commutation advance is generated. The commutation is applied using a timer countdown. The timer countdown period is calculated using the time between two particular commutation edges in the previous step, i.e. there is a table of times for each commutation sector. Owing to motor geometry inaccuracy (Hall sensors and winding position), it is necessary to store timing information for each commutation sector.

In the case of a higher voltage at the variable DC link six-step inverter input, the brake resistance is turned on to reduce voltage. When the voltage reaches a normal level, the brake resistance is turned off.

In the case of overvoltage, undervoltage, overcurrent or incorrect commutation edges within 200 commutations, the signals for the variable DC link six-step inverter and for the 3-phase inverter are disabled and the fault state is displayed.

Chapter 4
Hardware

4.1 Hardware Implementation

The application runs on Freescale's motor control MC56F8013 Controller Board, Freescale's 3-Phase Power Stage with DC/DC Inverter Lite, and a 24V BLDC motor with Hall sensors and high speed impeller. Both boards are integral parts of Freescale's set of embedded motion control development tools. The application hardware system configuration is shown in Figure 4-1.

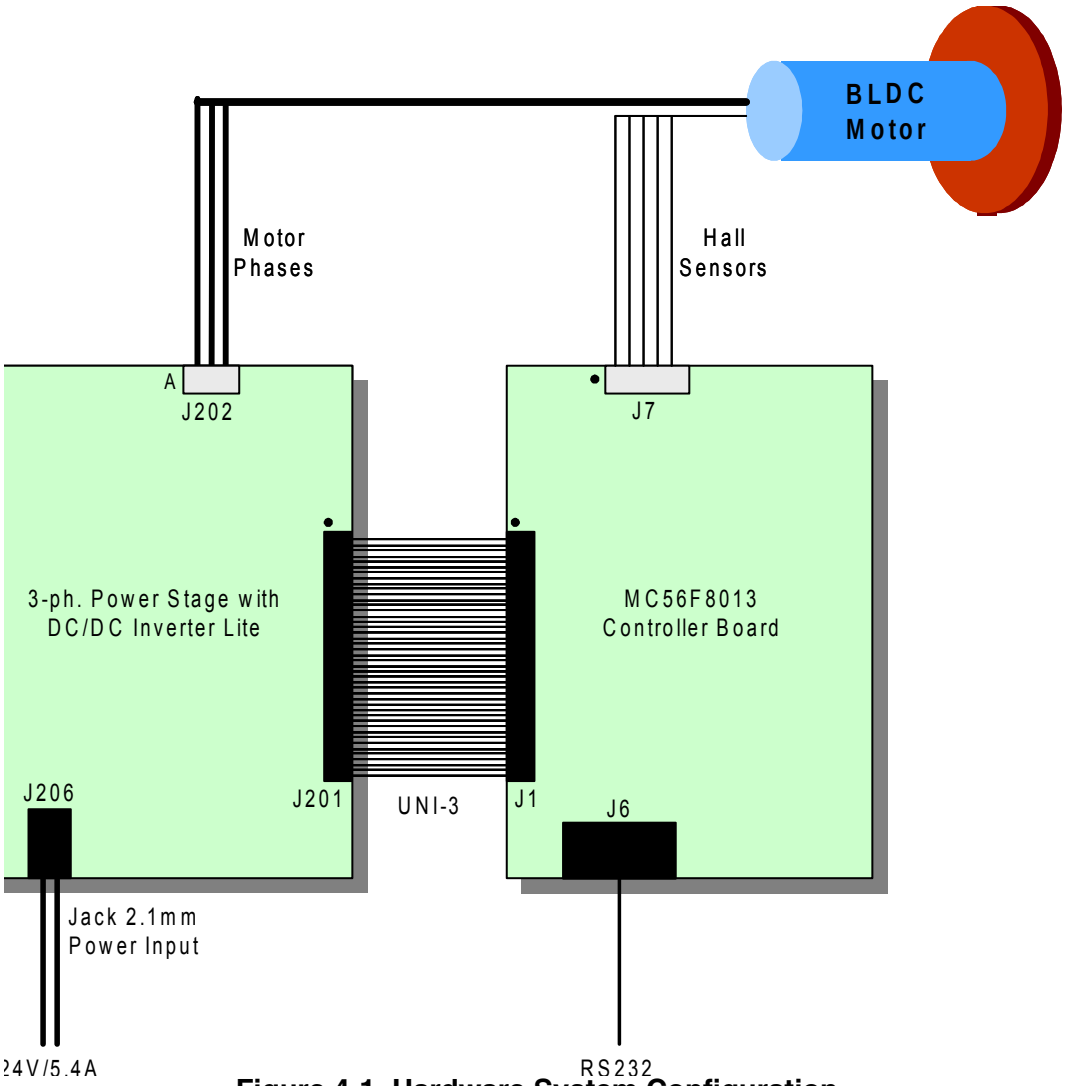


Figure 4-1. Hardware System Configuration

All system parts are supplied and documented in these references:

- MC56F8013 Controller Board:
  Using Freescale's MC56F8013 as the controller
  Supplied as MC56F8013 Controller Board
  Described in the *MC56F8013 Controller Board User's Manual*
- 3-Phase Power Stage with DC/DC Inverter Lite:
  Using Freescale's MC33883 MOSFET pre-drivers
  Supplied as 3-Phase Power Stage with DC/DC Inverter Lite
  Described in the *3-Phase Power Stage with DC/DC Inverter User's Manual*

A detailed description of each individual board can be found in the appropriate user manual, or on the Freescale web site http://www.freescale.com. The user manuals include a schematic of the board, a description of individual function blocks, and a bill of materials (parts list).

4.2 MC56F8013 Controller Board

The MC56F8013 controller board is based on an optimized PCB and power supply design. It demonstrates the abilities of the MC56F8013 and provides a hardware tool to help in the development of applications using the MC56F8013.

The MC56F8013 controller board is an evaluation module type of board; it includes an MC56F8013 part, encoder interface, tacho-generator interface, communication options, digital and analog power supplies, and peripheral expansion connectors. The expansion connectors are for signal monitoring and user feature expandability. Test pads are provided for monitoring critical signals and voltage levels.

The MC56F8013 controller board is designed for the following purposes:

- To allow new users to become familiar with the features of the MC56F801x architecture.
- To serve as a platform for real-time software development. The tool suite allows you to develop and simulate routines, download the software to on-chip memory, run the software, and debug it using a debugger via the JTAG/OnCE™ port. The breakpoint features of the OnCE port let you specify complex break conditions easily and execute your software at full-speed, until the break conditions are satisfied. The ability to examine and modify all user accessible registers, memory, and peripherals through the OnCE port simplifies considerably the task of the developer.
- To serve as a platform for hardware development. The hardware platform enables external hardware modules to be connected. The OnCE port's unobtrusive design means all of the memory on the digital signal controller chip is available to the user.

The MC56F8013 Controller Board facilitates the evaluation of various features present in the MC56F8013. The MC56F8013 Controller Board can be used to develop real-time software and hardware products based on the MC56F8013. The MC56F8013 Controller Board provides the features necessary to write and debug software, demonstrate the functionality of that software, and to interface with the customer's application specific device(s). The MC56F8013 Controller Board is flexible enough to allow full exploitation of the MC56F8013's features to optimize the performance of the user's end product. See Figure 4-2.

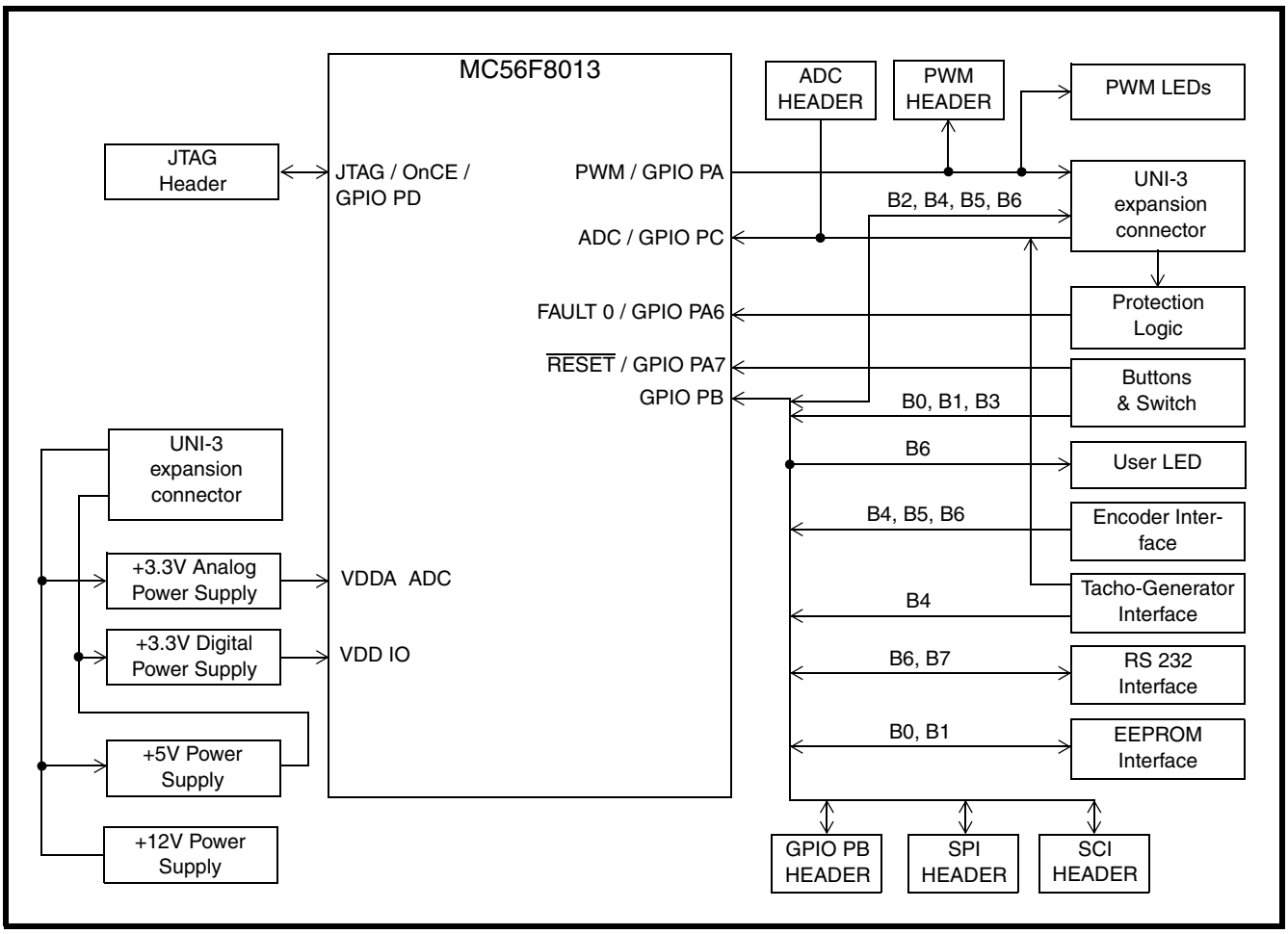


Figure 4-2. Block Diagram of the MC56F8013 Controller Board

4.3 3-Phase Power Stage with DC/DC Inverter Lite

Freescale Semiconductor's embedded motion control series 3-Phase Power Stage with DC/DC Inverter Lite is a 12V – 42V, 10A, surface-mount power stage. In combination with one of the embedded motion control series control boards, it provides a software development platform allowing algorithms to be written and tested without the need to design and build a power stage. It supports algorithms that use Hall sensors, and encoder and back EMF (electromotive force) signals for sensorless control.

The 3-Phase Power Stage with DC/DC Inverter Lite does not have any overcurrent protection independent of the control board; therefore, care in its setup and use is required if a lower impedance motor is used. Current measuring circuitry is set up for ±14.025A full scale. In a 25° ambient operation at up to 9A continuous RMS (12A for 10 seconds), output current is within the board's thermal limits.

Input connections are made via 40-pin ribbon cable connector J201. Power connections to the motor are made on a 3-way output connector J202. Phase A, phase B, and phase C are labeled on the board. The input current requirements are met by a single DC power supply capable of supplying 5A; however, it is recommended to use a more powerful supply. The voltage requirements are met by a power supply of 12V – 42V. The voltage should be within these limits. The board will sustain at least 9V, with maximum

of 50V (depending on the populated components rating). The input power is supplied by means of a 2.1mm jack connector J206.

Table 4-1. Electrical Characteristics of the Power Stage

Characteristic	Symbol	Min	Typ	Max	Units
Power Supply Voltage	Vdc	9	12, 24, 42	50	V
Quiescent Current(1)	I_{CC}	—	1.7	—	mA
Quiescent Current: +5V Generation on(1)	I_{CC5V}	—	4.8	—	mA
Quiescent Current: +15V Generation on(1)	I_{CC15V}	—	5.9	—	mA
Quiescent Current: +5V, +15V Generation on(1)	I_{CCSPL}	—	8.9	—	mA
Quiescent Current: +5V, +15V, Drivers On Signal(1)	I_{CCALL}	—	30.0	—	mA
Min Logic 1 Input Voltage	V_{IH}	2.4	—	—	V
Max Logic 0 Input Voltage	V_{IL}	—	—	0.8	V
Input Logic Resistance	R_{In}	—	4.7	—	kΩ
Analog Output Range	V_{Out}	0	—	3.3	V
Bus Current Sense Voltage	I_{Sense}	—	118	—	mV/A
Bus Current Sense Offset	I_{offset}		1.65		V
Bus Voltage Sense Voltage	V_{Bus}	—	153	—	mV/V
Bus Voltage Sense Offset	V_{offset}		0.2		V
Power MOSFET On Resistance	$R_{DS(On)}$	0.25	0.85	1.4	mΩ
Continuous Output Current(2)	I_D	—	9	12	A
Pulsed Output Current	I_{DM}	—	—	50	A
Total Power Dissipation (per MOSFET)(2)	P_D	—	1.85	3.75	W
Required Dead Time (generated by processor)	t_{off}	200	400	—	ns

1. Measured with the input power of 24V.
2. The values are measured at 25°C, for other temperatures the values may be different.

4.4 Motor Specifications — Example

The motor used in this application is a high-speed, low-inductance 24V BLDC motor equipped with Hall sensors. The motor has the following specifications:

Table 4-2. Specifications of the Motor and Hall Sensors

Motor Specification:	Motor Type:	3-Phase BLDC Motor 2-Poles
	Speed Range:	< 38000 RPM
	Line Voltage:	24V
	Phase Current:	<5A
Position Sensor Specification:	Sensor 1 Type:	3-Phase Hall Sensors
	Sensor 2 Type:	None

Chapter 5
Software Design

5.1 Introduction

This section describes the design of the drive's software blocks. The software description comprises these topics:

- Main Data Flow Chart
- Software Implementation
- Scaling of Quantities
- FreeMASTER Software

5.2 Main Data Flow Chart

The control algorithm of a closed-loop BLDC drive is described in Figure 5-1. The individual processes are described in the following sections.

5.2.1 Speed Control

Speed control starts with the `mfwOmegaRequiredMech` variable. This variable is remotely set within allowed limits by the FreeMASTER software on a PC. The variable `mfwOmegaRequiredMech` is fed to the ramp algorithm periodically performed in the timer compare interrupt. It is calculated every 10ms. The predefined ramp is 10000 RPM per 100ms. The ramp algorithm generates the `fwDesiredSpeed` variable input to the speed PI controller as a reference value. The measured speed provides a second input to this controller. The difference between these two values is the speed error. The speed PI controller generates the desired variable DC link six-step inverter output voltage `fwDesiredVoltage`. The commutation vector is calculated with respect to the polarity of the desired voltage, while its absolute value is fed to the voltage PI controller as `mfwDesiredDCDCVoltage`.

If the actual speed absolute value is smaller than 4600 RPM and the desired voltage is smaller than 2V, the required speed is set to 0, all bottom MOSFETs are turned on, and the motor is braked (the `muwwZeroDCDCVoltage` variable is set to 1).

The system contains two speed PI controllers, one for the range 15000 to 40000 RPM created for an acceleration of 15000 RPM per 100ms, and a second for the range 0 to 15000 RPM constructed with an acceleration of 10000 RPM per 300ms. The speed controller is calculated every 1ms. The hysteresis between these two PI controllers is 1500 RPM, meaning if the speed goes up, the higher speed PI controller is switched on at the threshold of 15000 RPM, and when the speed goes down, the lower speed PI controller is switched on at a speed of 13500 RPM.

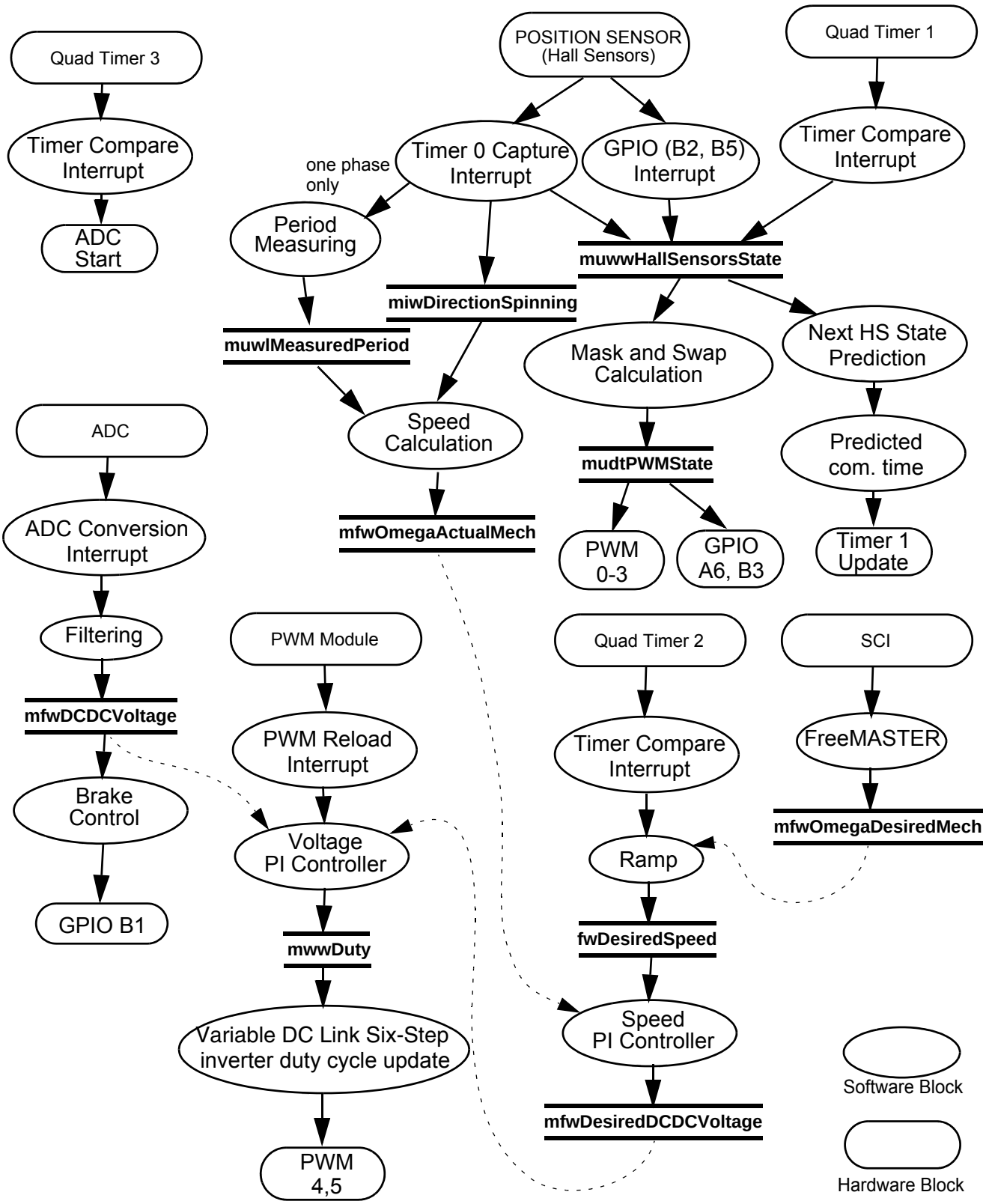


Figure 5-1. Main Data Flow

5.2.2 Voltage Control

The voltage control is based on the PWM reload interrupt established at a frequency of 100kHz, illustrated in Figure 5-2.

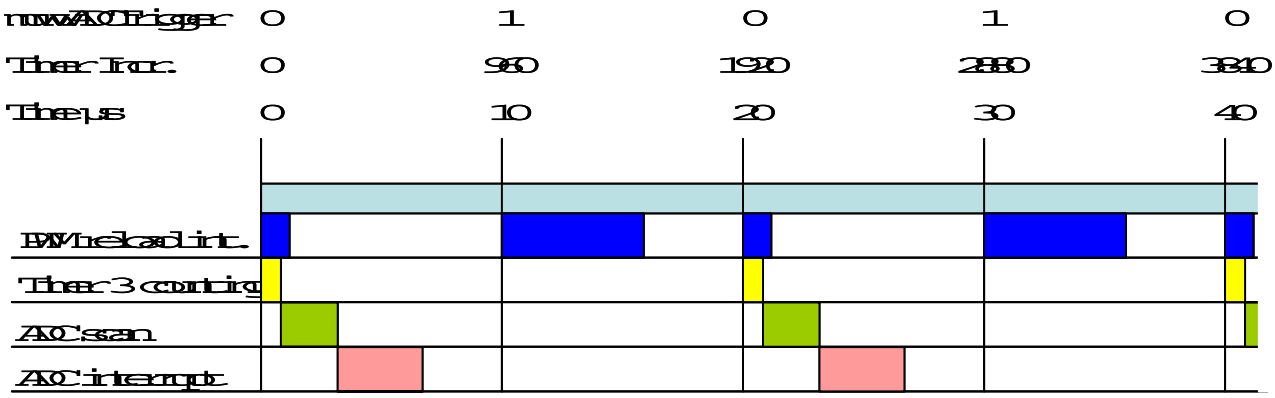


Figure 5-2. Voltage Control Scheduling

As stated, the PWM reload generates an interrupt every 10µs. The reload serves to synchronize some processes to the variable DC link six-step inverter PWM period:

- The ADC start is situated at 1µs after the beginning of every second PWM period by means of timer 3. This timer is started at the beginning of the PWM reload period. When timer 3 reaches its compare period, it triggers the ADC scan. The PWM, timer and ADC are connected on a hardware level, so no software interaction is required.
- When the ADC measures the desired values, it generates an interrupt where the measured values are filtered and stored for further processing.
- When the PWM reload interrupt is called, the `muwwADCTrigger` is inverted (0/1). This variable determines if the ADC is started in the current PWM period (0) and/or if the voltage PI controller is calculated (1).

Timer 3 does not contain any routine attached to its interrupt, and serves only to start the ADC conversion precisely 90 increments after the start of the PWM period. When the ADC finishes the conversion it reads and filters the measured values. The ADC measurement uses only four channels in the simultaneous mode due to the shortage of time. So ADC channel 0 is used for the variable DC link six-step inverter output voltage measurement each ADC period (50kHz), and channel 1 is shared by the DC bus input voltage and motor current that are then measured at a frequency of 25kHz. Channels 4 and 5 are used to measure the voltage and current zero references. These two references are read and filtered until the following PWM reload interrupt, when the voltage PI controller value is not calculated. However, the filtered references are updated in the ADC offset registers in the period when the voltage PI controller value is calculated

So, the variable DC link six-step inverter output voltage, DC bus input voltage and motor current are measured. The measured values are subtracted from the measured references and then filtered. The subtraction is performed by hardware using the ADC offset registers. If the measured DC bus voltage is greater than 26V, the braking resistance MOSFET is turned on, and is turned off when the voltage falls below 25V. If the voltage is higher than 25V or lower than 18V for longer than 100ms, the overvoltage or undervoltage flag is generated. The overcurrent protection averages the measured current over the interval of 16384 values. If this averaged current is higher than 3.5A the overcurrent flag is generated.

As stated, the voltage PI controller calculation is performed every second PWM reload interrupt routine call, meaning it is calculated at a frequency of 50kHz (every 20µs). The measured and filtered variable DC link six-step inverter output voltage is fed to the PI controller. The difference between the desired voltage `mfwDesiredDCDCVoltage` and the measured voltage `mfwDCDCVoltage` is the error. This controller's output is just the duty cycle for the variable DC link six-step inverter MOSFETs `mwwDuty`. Its absolute value is written either into PWM channel 4 or 5. If it is positive, channel 4 is loaded with the duty cycle value and channel 5 is loaded with 0; vice versa if it is negative.

5.2.3 Commutation

On each new edge of the Hall sensor signals, a capture interrupt (phase A) and/or a GPIO interrupt (phase B, C) is called. The interrupt routine saves the actual Hall sensor state to `muwwHallSensorsState`. The `muwwHallSensorsState` variable is input to the mask and swap calculation, determining the final shape of the output voltage. The output variable `mudtPWMState` is written directly to the PWM block, channels 0 to 3, and GPIO A6 and B3. The next task performed by an interrupt routine is the calculation of the spin direction. The result, `miwDirectionSpinning`, is used for the speed calculation.

For speeds greater than 500 RPM, the system calculates the next Hall sensors commutation state in every commutation interrupt. When the new commutation edge arrives, the system compares it with this predicted state. If the real Hall sensor edge signal is different from predicted, the interrupt routine ends and no commutation is performed. This means the commutation is performed as soon as the correct Hall sensor signal arrives.

This routine also stores in the table the time between two commutation edges. Each commutation sector has its own table record. If the speed is greater than 11600 RPM, commutation is advanced. Once the controlled commutation advance technique is turned on, it is turned off when the speed goes below 8700 RPM.

The advance period is set by the `muwwCommutationAdvance` variable with a precision of 100ns. It is set to 40µs, meaning the commutation is performed 40µs before the commutation edge arrives. It improves the motor spinning and torque efficiency. This method uses timer 1, updated and synchronized on every commutation Hall sensor edge.

If the system does not receive the predicted commutation edge within 200 commutations, a Hall sensors cable fault is generated. During this period the system commutates using the timer and commutation times table.

5.2.4 Velocity Calculation

The Hall sensors generate streams of pulses captured (phase A) by the timer 0 input capture function. The speed can be calculated knowing the timer frequency and the time between two Hall sensor edges. The application uses the two timers' frequencies to enlarge the RPM range. The first frequency is 4MHz for the range 3700 to 38000 RPM; the second frequency is 250kHz for the range 250 to 4700 RPM. The timer frequency is derived from the 32MHz bus clock by applying the divider. For 4MHz the divider is 8, and for 250kHz it is 128.

So, this divider is adjusted by the current speed. The motor starts with the divider at 128, allowing the speed to be measurable from 250 RPM. As the speed goes up, the divider is switched to 8 at the 3700 RPM threshold. The system keeps this divider within the range up to 38000 RPM. When the speed goes down, the divider is switched to 128 at the 4200 RPM threshold.

5.3 Software Implementation

The general software diagram incorporates the main routine (Main) entered from reset and the interrupt states (see Figure 5-3).

The main routine initializes the digital signal controller and the application, then it enters an infinite background loop. The background loop contains an application state machine.

The following interrupt service routines are utilized:

- PWM reload – voltage PI controller calculation and ADC references processing, PWM update
- ADC conversion complete – reads and filters measured values, braking resistance and fault control
- Timer 0 input capture and overflow – commutation and speed calculation
- GPIO B5 and B2 – commutation
- Timer 2 compare – speed PI controller calculation, ramp calculation
- Timer 1 compare – commutation advance
- SCI – services communication with the FreeMASTER software

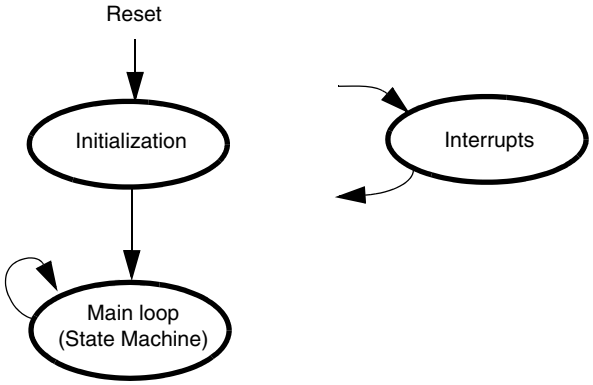


Figure 5-3. State Diagram — General Overview

5.3.1 Initialization

The Main routine initializes the DSP:

- Disables interrupts
- Initializes PLL
- Disables COP and LVI
- Initializes the system integration module
  - enables PWM, SCI, timer, ADC modules
  - connects the timer 3 input to the PWM reload_sync signal
  - sets the timer clock source to 1x bus clock
  - sets the PWM clock source to 3x bus clock
- Initializes GPIO A and B modules
  - GPIO A6 and B3 as outputs for PWM 4 and 5 MOSFETs
  - GPIO B2 and B5 as inputs for Hall sensor signals
  - GPIO B0 as the output for the brake resistance control

- Initializes the SCI for FreeMASTER communication
- Initializes the interrupt controller
- Initializes the ADC
- Initializes timer 3 for ADC sync to PWM reload
- Initializes timer 1 for commutation advance
- Initializes timer 0 for commutation and speed evaluation
- Initializes the PWM module:
  - Edged-aligned independent PWM mode, positive polarity
  - PWM modulus 960 – defines the PWM frequency as 100kHz
  - PWM reload – every opportunity
  - Channels 0 – 3 for the 3-phase inverter MOSFETs
  - Channels 4 – 5 for the variable DC link six-step inverter MOSFETs
- Initializes the voltage PI controller parameters
- Reads the Hall sensors signals and evaluates the rotor position
- Clears GPIO B pending flags
- Initializes timer 2 for ramp and speed control algorithms
- Initializes the speed PI controllers parameters
- Initializes FreeMASTER
- Pre-sets the first state as the INIT state
- Enables the interrupts

5.3.2 Interrupts

The interrupts have the following functions:

- PWM reload interrupt – triggered every PWM reload. On an even occurrence, the ADC zero references are updated in the ADC offset registers and the voltage PI controller is calculated. PWM channels 4 and 5 are updated by the duty cycle, calculated by the PI controller. The ADC is enabled so as to start in the next state. On an odd occurrence, the voltage and current ADC zero references are read and filtered.
- ADC conversion complete interrupt – the ADC is stopped for the next state. The variable DC link six-step inverter output voltage is read and filtered. Then, depending on the odd or event state, either the DC bus input voltage or the motor current is read and filtered. The overvoltage and undervoltage flags are generated according to the measured voltage level, and/or the overcurrent flag is generated according to the measured motor current level. Brake resistance is turned on and off depending on the DC bus voltage level.
- Quad timer 0 interrupt – this interrupt has two sources. One of them is the overflow event. In this event, the routine will remember that the timer overflowed, as information for further speed calculation. The other source is the input capture signal. This event is used for commutation and also for the speed calculation. This routine also saves the Hall sensor edge time of each sensor and uses it to calculate the time of the next advanced commutation.
- GPIO B interrupt – this interrupt routine has two sources, pins 5 and 2. Both are connected to the Hall sensor signals and serve for commutation.

- Quad timer 2 interrupt – this interrupt is generated every 1ms. It generates the speed ramp and calculates the speed PI controller. It also turns on and off the commutation control features, such as prediction of the next Hall sensor state and commutation advance control.
- Quad timer 1 interrupt – this interrupt occurs when the timer reaches the preset compare value loaded in the quad timer 0 interrupt. This compare event causes advanced commutation and calculates the time of the next advanced commutation, for the case where the Hall sensor edge does not arrive in the next state.

5.3.3 Drive State Machine

The drive can be in one of the following states, illustrated in Figure 5-4, also showing transition conditions among the drive states.

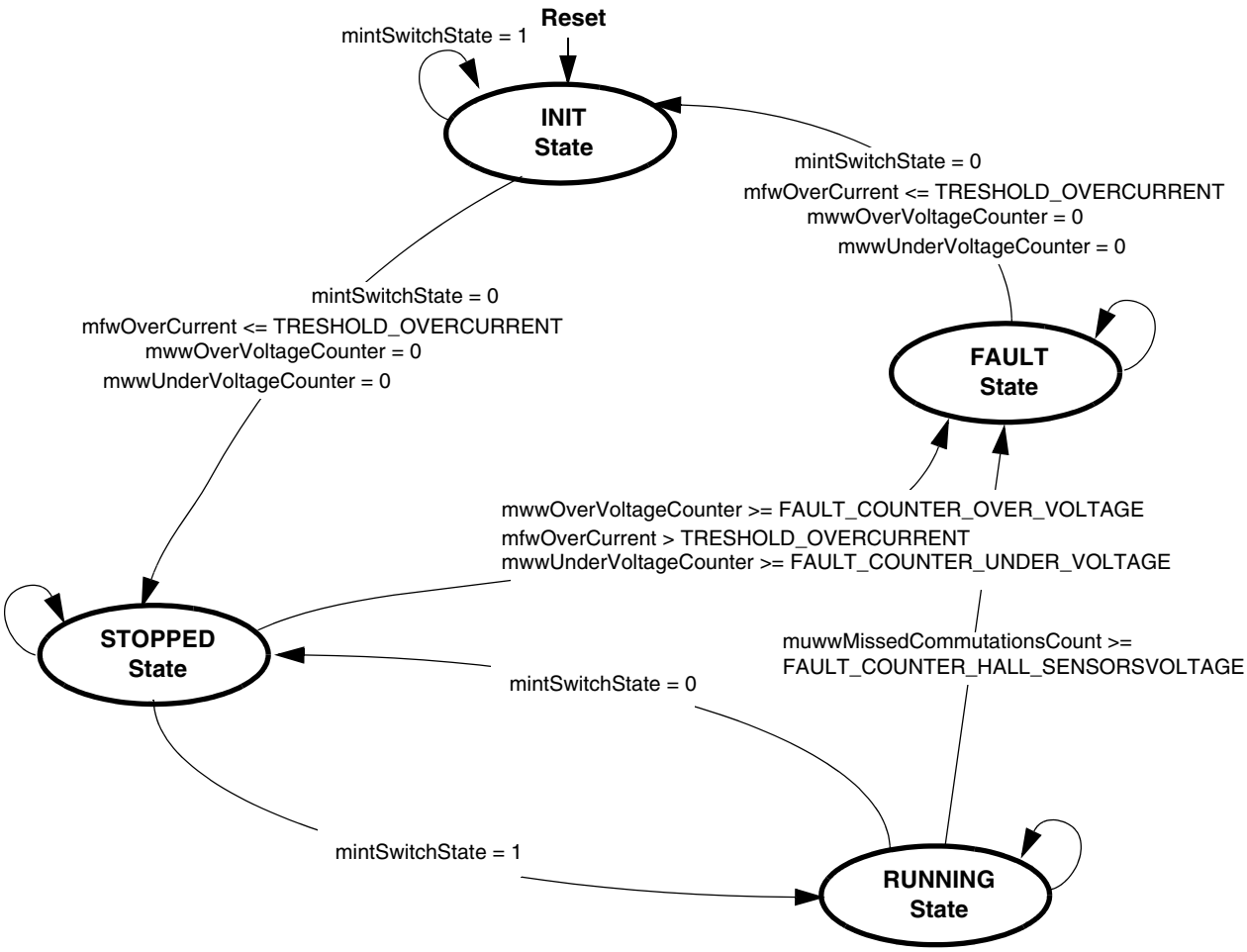


Figure 5-4. Drive State Machine Transitions

5.3.3.1 INIT State

The INIT state initializes several state variables and sets up some peripherals:

- Turns off the MOSFET pre-drivers by GPIO B0
- Disables the MOSFET PWM signals by forcing them into tri-state (PWM 0 – 5, GPIO B2, B5)
- Disables the brake resistance control pin and forces it into tri-state (GPIO B1)
- Resets the required speed, desired variable DC link six-step inverter output voltage, variable DC link six-step inverter PI controller integral portion, and fault occurrence variables.
- If the switch is turned off and no under or overvoltage or overcurrent condition is present the STOPPED state is entered.

5.3.3.2 STOPPED State

The application remains in this state as long as the switch is turned off. If an undervoltage, overvoltage or overcurrent fault is present, the FAULT state is entered. The MOSFET pre-drivers are still turned off so no voltage should be present at the variable DC link six-step inverter output. The following variables and peripherals are initialized:

- Resets the required speed and the desired variable DC link six-step inverter output voltage and low speed PI controller integral portion variables.
- If the switch is turned on, the application enters the RUNNING state. At the same time, the variable DC link six-step inverter duty cycle variable is set to 0, the MOSFET pre-drivers are switched on by GPIO B0, all the bottom MOSFETs are turned on and the top MOSFETs are turned off, PWM and GPIO B2 and B5 outputs are enabled, and the brake resistance output pin is enabled.

5.3.3.3 RUNNING State

The application remains in this state as long as the switch is turned on. If an undervoltage, overvoltage, overcurrent, or Hall sensor signal fault is present, the FAULT state is entered. The MOSFET pre-drivers are turned on. In this state, the inverters are controlled and the motor can be driven. If the switch is turned off, the application enters the STOPPED state. At the same time, the PWM and GPIO B2 and B5 output pins are disabled, forced into tri-state along with the brake resistance control pin GPIO B0.

5.3.3.4 FAULT State

This state is entered when a fault is generated by an overvoltage, undervoltage, overcurrent, or Hall sensor signal. In this state, the PWM and GPIO B2 and B5 output pins are disabled, forced into tri-state along with the brake resistance control pin GPIO B0. The MOSFET pre-drivers are turned off by GPIO B0. The required speed and desired variable DC link six-step inverter output voltage variables are reset. If the switch is turned off and no undervoltage, overvoltage or overcurrent condition is present, the INIT state is entered.

5.4 Scaling of Quantities

The BLDC motor control application uses a fractional representation for all real quantities except time. The N-bit signed fractional format is represented using 1.[N-1] format (1 sign bit, N-1 fractional bits). Signed fractional numbers (SF) lie in the following range:

$$-1.0 \leq SF \leq +1.0 - 2^{-[N-1]} \tag{5-1}$$

For word and long-word signed fractions, the most negative number that can be represented is -1.0, whose internal representation is $8000 and $80000000, respectively. The most positive word is $7FFF or $1.0 - 2^{-15}$, and the most positive long-word is $7FFFFFFF or $1.0 - 2^{-31}$.

The following equation shows the relationship between real and fractional representations:

$$\text{Fractional Value} = \frac{\text{Real Value}}{\text{Real Quantity Range}} \tag{5-2}$$

where:

- Fractional Value is a fractional representation of the real value [Frac16]
- Real Value is the real value of the quantity [V, A, RPM, etc.]
- Real Quantity Range is the maximum range of the quantity, defined in the application [V, A, RPM, etc.]

5.4.1 Voltage Scaling

The DC bus voltage and variable DC link six-step inverter output voltage sense is defined by the following equation:

$$\text{voltage} = \frac{V_{MEASURED}}{V_{MAX}} \cdot 32767 \tag{5-3}$$

Where:

- voltage = variable of measured voltage
- $V_{MEASURED}$ = measured voltage
- V_{MAX} = max. measurable voltage (V_{MAX} = 31V for the 3-Phase Power Stage with DC/DC Inverter Lite)

5.4.2 Current Scaling

The motor current sense is defined by the following equation:

$$\text{current} = \frac{I_{MEASURED}}{I_{MAX}} \cdot 32767 \tag{5-4}$$

Where:

- current = variable of measured current
- $I_{MEASURED}$ = measured current
- I_{MAX} = max. measurable current (I_{MAX} = 14.025A for the 3-Phase Power Stage with DC/DC Inverter Lite)

5.4.3 PI Controller Parameters

The PI controller parameters consists of the gain and gain scale parameters of the proportional and integral constants. The proportional, or integral gain parameter, lies in the fractional number 0 to 1 (representing 0 to 32767) and the gain scale parameter shifts the particular gain to the right if positive, or to the left if negative. The gain scale number represents the number of shifts.

The limit parameters represent the minimum and maximum outputs from the PI controller. The output will be within these limits.

5.4.4 Speed Calculation

The speed coefficient scaling is as follows:

1. The maximum speed of the motor is 36200 RPM, so the software maximum speed is set with small reserve as

$$\mathrm{vmax} = 38000\mathrm{RPM} \tag{5-5}$$

   And for the lower speed maximum, use the maximum higher speed divided by 8, because a division by 8 can be performed very easily by register shifting, and is not very time consuming. Therefore:

$$\mathrm{vmax_low} = \frac{38000\mathrm{RPM}}{8} = 4750\mathrm{RPM} \tag{5-6}$$

2. We have to know the number of Hall sensor edges per revolution. The motor has one pole-pair, meaning six edges per revolution (three rising, three falling for the three Hall sensors). But this application uses only one Hall sensor, so there should be two edges per revolution. As it is a very fast motor, it is enough to use just one edge (rising) for the speed calculation. So, the final number of edges per revolution is one. Therefore:

$$\mathrm{position_difference} = \frac{1}{\mathrm{edges}} = \frac{1}{1} = 1 \tag{5-7}$$

3. A 16-bit timer is used, meaning it overflows after 65535 increments. As mentioned above, for the higher speeds the 8 divider is used, so the frequency is 32MHz/8 = 4MHz. The time period for the timer overflow is then

$$\mathrm{max_period} = \frac{65535}{\mathrm{timer_freq}} = \frac{65535}{4\mathrm{MHz}} = 16.38375\mathrm{ms} \tag{5-8}$$

   For the lower speed calculations, the frequency is 32MHz/128 = 250kHz.. So the time period for the timer overflow is then

$$\mathrm{max_period_low} = \frac{65535}{\mathrm{timer_freq}} = \frac{65535}{250\mathrm{kHz}} = 262.14\mathrm{ms} \tag{5-9}$$

4. Knowing the maximum timer period, we can determine the minimum possible speed in RPM. So the minimum speed limits are

$$\mathrm{vmin} = 60\mathrm{s}\cdot\mathrm{min}^{-1}\cdot\frac{\mathrm{position_difference}}{\mathrm{max_period}} = 60\mathrm{s}\cdot\mathrm{min}^{-1}\cdot\frac{1}{16.38375\mathrm{ms}} = 3662\mathrm{RPM} \tag{5-10}$$

$$\mathrm{vmin_low} = 60\mathrm{s}\cdot\mathrm{min}^{-1}\cdot\frac{\mathrm{position_difference}}{\mathrm{max_period_low}} = 60\mathrm{s}\cdot\mathrm{min}^{-1}\cdot\frac{1}{262.14\mathrm{ms}} = 237\mathrm{RPM} \tag{5-11}$$

5. Now we can calculate the coefficient for the speed calculation. Signed 16-bit fractional arithmetic is used, so the maximum number can be 32767. The coefficients are then

$$\text{mwwOMEGA_ACTUAL_MECH_CONST} = 32767 \cdot \frac{\text{vmin}}{\text{vmax}} = 32767 \cdot \frac{3662\text{RPM}}{38000\text{RPM}} = 3158 \quad (5\text{-}12)$$

$$\text{mwwOMEGA_ACTUAL_MECH_CONST_LOW} = 32767 \cdot \frac{\text{vmin_low}}{\text{vmax_low}} = 32767 \cdot \frac{237\text{RPM}}{4750\text{RPM}} = 1579 \quad (5\text{-}13)$$

6. The speed is then calculated simply using the information of timer increments between two Hall sensor edges, so

$$\text{mfwOmegaActualMech} = \frac{\text{mwwOMEGA_ACTUAL_MECH_CONST}}{\text{counted_edges}} \quad (5\text{-}14)$$

   However, since the lower speed limit is set by the higher speed limit divided by 8, the lower speed result must be divided by 8 (meaning shifted by 3 to the right):

$$\text{mfwOmegaActualMech} = \frac{\text{mwwOMEGA_ACTUAL_MECH_CONST_LOW}}{\text{counted_edges}} >> 3 \quad (5\text{-}15)$$

7. And the speed in RPM is as follows: 32767 corresponds to 38000 (`vmax`), so

$$\text{speed_in_RPM} = \frac{\text{mfwOmegaActualMech}}{32767} \cdot \text{vmax} \quad (5\text{-}16)$$

5.5 FreeMASTER Software

The FreeMASTER software was designed to provide an application debugging, diagnostic and demonstration tool for the development of algorithms and applications. It runs on a PC connected to the controller board via an RS232 serial cable. A small program resident in the digital signal controller communicates with the FreeMASTER software to parse commands, return status information to the PC, and process control information from the PC. FreeMASTER software, executing on a PC, uses part of Microsoft Internet Explorer as the user interface.

The FreeMASTER software is part of the Freescale Semiconductor Quick Start and may be selectively installed during the Quick Start installation.

The baud rate of the SCI communication for this application is 14400 baud. It is set automatically by the FreeMASTER software driver and can be changed if necessary.

A detailed description of the FreeMASTER software is provided in the dedicated *FreeMASTER for Embedded Applications* documentation.

The 3-phase BLDC motor control application utilizes FreeMASTER software for remote control from the PC. It enables the user to:

- Control starting and stopping
- Set the motor speed

Variables read by the FreeMASTER software and displayed to the user are:

- Required motor speed and actual motor speed
- Application operational mode
- Start/stop status
- DC bus voltage, variable DC link six-step inverter output voltage, motor current
- Overvoltage, undervoltage, overcurrent and Hall sensor cable faults
- Hall sensor state using the on-line scope (The Hall sensor state must be watched at very low speeds because of the RS232 serial communication speed limitation.)

The FreeMASTER software Control Page is illustrated in Figure 6-1. The profiles of the required and actual speeds are available in the Speed Scope window.

Chapter 6
Application Setup

6.1 Application Description

The application runs on the Freescale MC56F8013. The software generates all signals needed to control the variable DC link six-step inverter and 3-phase inverter according to the user-required inputs, measured and calculated signals.

The concept of the BLDC drive incorporates the following hardware components:

- BLDC motor set
- 3-Phase Power Stage with DC/DC Inverter Lite
- MC56F8013 Controller Board

The BLDC motor incorporates a 3-phase 24V BLDC motor with an attached high-speed impeller. The BLDC motor has two poles. The Hall sensors are mounted inside the motor. The detailed motor specifications are listed in Table 4-2.

The drive can be controlled from the FreeMASTER software only:

- To start/stop the drive application, click on the On/Off switch.
- Set the required speed by clicking on the speed gauge.

Measured quantities:

- DC bus voltage
- Motor current
- Rotor speed

The faults used for drive protection:

- Overvoltage
- Undervoltage
- Overcurrent
- Hall sensors cable error

6.1.1 Control Process

After reset, the drive enters the INIT state, in which the application is initialized; it then goes into the STOP state. In the STOP state, all the control signals are disabled and the motor cannot spin. The operation mode can be changed to the RUN state from the FreeMASTER software by clicking on the On/Off button.

Speed is controlled in the RUN state using the `mfwOmegaRequiredMech` variable. This variable is set within allowed limits remotely by the FreeMASTER software on PC. The variable `mfwOmegaRequiredMech` is fed to the ramp algorithm. The predefined ramp is 10000 RPM per 100ms. The ramp algorithm generates the `fwDesiredSpeed` variable input to the speed PI controller as a reference value, and a second input to this controller is the measured speed. The difference between these two values is the speed error. The speed PI controller generates the desired variable DC link

six-step inverter output voltage `fwDesiredVoltage`. The commutation vector is calculated with respect to the polarity of the desired voltage, while its absolute value is fed to the voltage PI controller as `mfwDesiredDCDCVoltage`.

The system measures the variable DC link six-step inverter output voltage fed to the PI controller. The difference between the desired voltage `mfwDesiredDCDCVoltage` and the measured voltage `mfwDCDCVoltage` is the error. This controller's output is simply the duty cycle for the variable DC link six-step inverter MOSFETs `mwwDuty`. Its absolute value is written either to PWM channel 4 or 5. If it is positive, channel 4 is loaded with the duty cycle value and channel 5 is loaded with 0; vice versa if it is negative.

According to the Hall sensor state, and the desired direction of spinning, the MOSFETs of the 3-phase inverter are turned on and off and the motor spins.

6.1.2 Drive Protection

The DC bus voltage and motor current are measured during the control process. They protect the drive from overvoltage, undervoltage and overcurrent. All protection is performed by software.

The Hall sensor cable signals are read during running. If the sensors return an unidentified commutation vector, a Hall sensor cable fault is generated.

If any of the above mentioned faults occur, the variable DC link six-step inverter and 3-phase inverter control signals are disabled to protect the drive, and the application enters the FAULT state. At the same time, the MOSFET pre-drivers are disabled. If no overvoltage, undervoltage or overcurrent condition is present, the application can be switched from the FAULT state to the STOP state by switching off the switch.

Table 6-1. Motor Application States

Application State	Motor State	Pre-driver State	Gate Signals
Init	Stopped, gates tri-stated	Disabled	Tri-stated
Stopped	Stopped, gates tri-stated	Disabled	Tri-stated
Running	Spinning, gates active	Enabled	Logically active
Fault	Stopped, gates tri-stated	Disabled	Tri-stated

The following FreeMASTER software control actions are supported:

- Start the motor
- Stop the motor
- Set the required speed of the motor

The FreeMASTER software displays the following information:

- Required speed of the motor
- Actual speed of the motor
- Application status – INIT/STOP/RUN/FAULT
- DC bus voltage level
- Motor current
- Fault status – overvoltage, overcurrent, undervoltage, or Hall sensor cable error

Start the FreeMASTER software window's application, *bldc_hall_56F8013.pmp*. Figure 6-1 illustrates the FreeMASTER software control window for the application running.

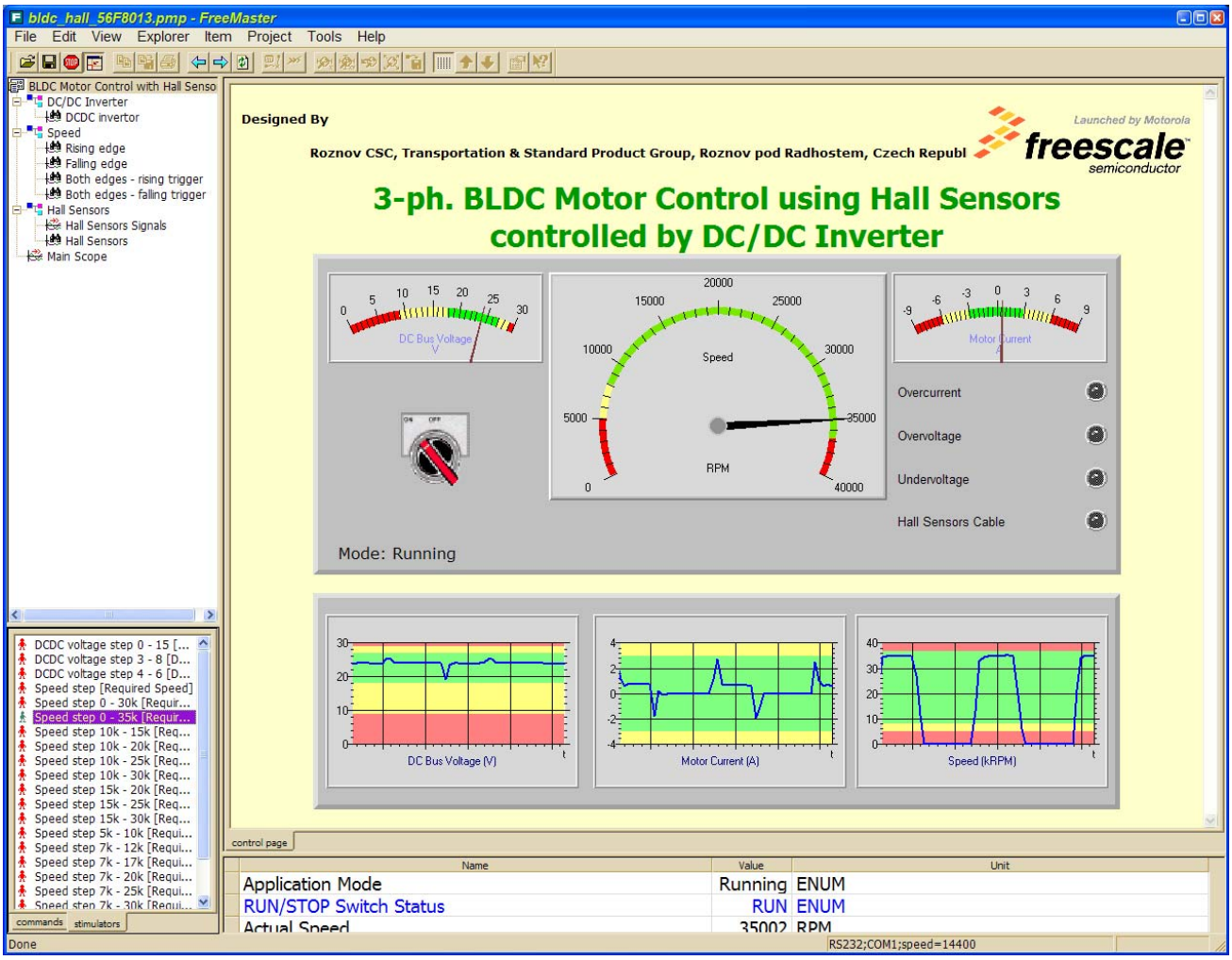


Figure 6-1. FreeMASTER Software Control Window

6.2 Application Set-Up

Figure 6-2 illustrates the hardware setup for the 3-Phase BLDC drive using variable DC link six-step inverter application. The controller board, power stage and motor are mounted on a plexiglass board.

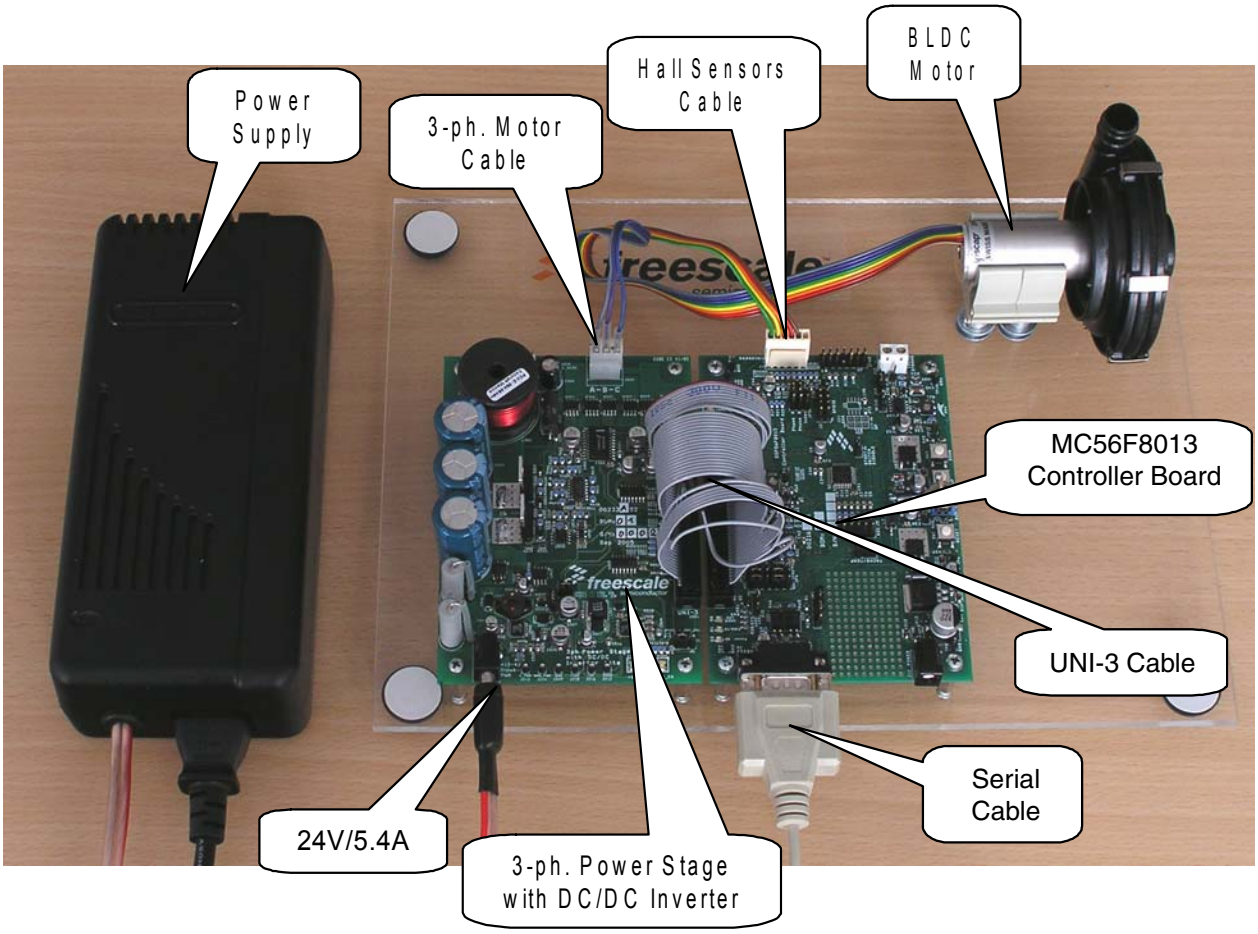


Figure 6-2. Setup of the BLDC Drive using DC/DC Inverter

For detailed information, see the *MC56F8013 Controller Board User's Manual* and the *3-Phase Power Stage with DC/DC Inverter Lite User's Manual***.** The serial cable is needed for the FreeMASTER software control.

The system consists of the following components:

- High speed 24V BLDC motor
- MC56F8013 controller board
- 3-Phase Power Stage with DC/DC Inverter Lite
- Serial cables – required for the FreeMASTER software tool only
- Parallel cable with JTAG converter– required for the Metrowerks CodeWarrior debugging and software loading

6.2.1 MC56F8013 Controller Board Application Setup

To execute the 3-Phase BLDC drive using variable DC link six-step inverter the MC56F8013 Controller Board and 3-phase Power Stage with DC/DC Inverter Lite require the strap settings shown in Figure 6-3 and Table 6-2, Table 6-3.

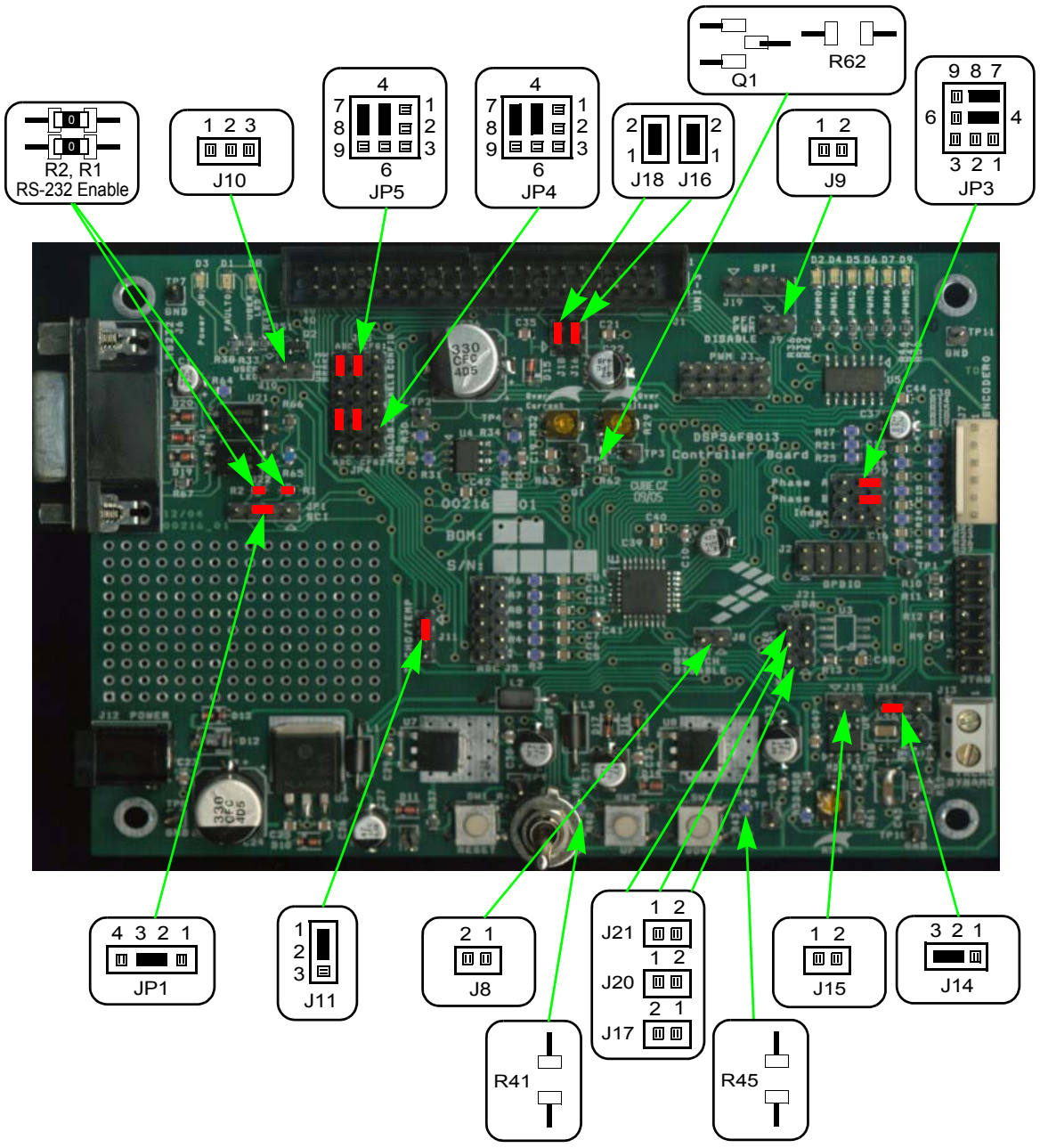


Figure 6-3. MC56F8013 Controller Board

Table 6-2. MC56F8013 Controller Board Jumper Options

#	Selector	Function	Connections
JP1	SCI	Full-duplex serial mode	2-3
	R1, R2	RS 232 interface enabled	R1, R2 present
JP3	Encoder / UNI-3 BEMFZCx	Hall sensor 1 to PB4, Hall sensor 2 to PB5	4-5, 7-8
JP4	PHBIS/BEMFB / I_IN	+1.65V current reference to ANB1 (UNI-3 phase B current)	4-5
	PHCIS/BEMFC / TEMP	+0.2V voltage reference to ANB2 (UNI-3 phase C current)	7-8
JP5	PHBIS / BEMFB	+1.65V current reference (phase B current) measurement selected	4-5
	PHCIS / BEMFC	+0.2V voltage reference (phase C current) measurement selected	7-8
J8	START Switch	START switch disconnected from PB3	open
J9	PFC PWM	UNI-3 PFC PWM disconnected from PB2	open
J10	USER LED / UNI-3 BRAKE	USER LED output disconnected	open
		UNI-3 BRAKE output disconnected	open
J11	TACHO / TEMP	DC bus voltage measurement (UNI-3 TEMP) -> ANA2 selected	1-2
J14	Tacho-dynamo measurement	Tacho-dynamo input -> digital output selected	2-3
J15	Tacho-generator	Tacho-generator digital output disconnected from PB4	open
J16	UNI-3 +5V	CB digital power supply from UNI-3 +5V	closed
J18	UNI-3 +15V	CB analog power supply from UNI-3 +15V	closed
J17	WP	Serial EEPROM memory is write protected	open
J20	SCL	Serial EEPROM memory SCL input disconnected from PB0	open
J21	SDA	Serial EEPROM memory SDA I/O disconnected from PB1	open

As the MC56F8013 Controller Board was not designed exactly for this application some additional operations must be provided:

- Wire connection between JP3.1 and J9.2 – to connect Hall sensor 3 to PB2
- Wire connection between JP4.6 and J2.1 – to connect PB0 to UNI-3 #32 (DRV_EN)
- Wire connection between JP5.6 and J3.8 – to connect PA6 to UNI-3 #39 (PWM_CT)
- Wire connection between JP5.9 and J2.4 – to connect PB3 to UNI-3 #40 (PWM_CB)
- Wire connection between J10.3 and J2.2 – to connect PB1 to UNI-3 #29 (BRAKE)
- Remove R45 – to disconnect SW3 and 3.3V pullup voltage
- Remove R41 – to disconnect SW2 and 3.3V pullup voltage
- Remove R62, Q1 – to disconnect fault and 3.3V pullup voltage

Table 6-3. 3-Phase Power Stage with DC/DC Inverter Lite Jumper Options

#	Function	Connections
JP401	Pre driver enabled by the UNI-3 signal	2-3
JP501	+5V voltage generation enabled	closed
JP502	+15V voltage generation enabled	closed

CAUTION

Do not enable +15V generation on the 3-Phase Power Stage with DC/DC Inverter without enabling +5V generation. The gate signals use buffers to convert from 3.3V logic to 5V logic. As the brake resistance pre-driver is always enabled, the absence of +5V could turn on the brake resistance.

Some signals must be swapped on the UNI-3 cable according to Table 6-4.

Table 6-4. UNI-3 Cable changes

Power Stage	Controller Board
9	39
11	40
31	9
33	11
39	Not connected
40	Not connected
Not connected	31
Not connected	33

6.3 Project Files

The 3-Phase BLDC drive using variable DC link six-step inverter application is composed of the following files:

- **...\bldc_hall_56F8013_qs21\bldc_hall_56F8013.c**, main program
- **...\bldc_hall_56F8013_qs21\bldc_hall_56F8013_qs21.mcp**, application project file
- **...\bldc_hall_56F8013_qs21\ApplicationConfig\appconfig.h**, application configuration file
- **...\bldc_hall_56F8013_qs21\SystemConfig\SDM_pFlash.cmd**, linker command file for Flash
- **...\bldc_hall_56F8013_qs21\Freemaster\bldc_hall_56F8013.pmp**, FreeMASTER software file

These files are located in the application folder.

- **...\ramp.c, .h**, source and header files for ramp generation
- **...\MCLIB56F800E_r2.0\MCLIB_56800ESDM.lib**, motor control algorithms library

All necessary Quick Start resources (algorithms and peripheral drivers) are part of the application project folder. All resources are copied into the following folder under the application folder so the libraries of the DSP56800E_Quick_Start are no longer required:

- **...\bldc_hall_56F8013_qs21\src\include**, folder for general C-header files
- **...\bldc_hall_56F8013_qs21\src\MC56F8013**, folder for the device specific source files, e.g. drivers
- **...\bldc_hall_56F8013_qs21\src\support\freemaster**, folder for FreeMASTER software source files

6.4 Application Build and Execute

When building the 3-Phase BLDC drive using variable DC link six-step inverter, an application running from *pFlash* is created. The project may be built by executing the *Make* command, illustrated in Figure 6-4. This builds and links the 3-Phase BLDC drive using variable DC link six-step inverter application and all required Metrowerks and Quick_Start libraries.

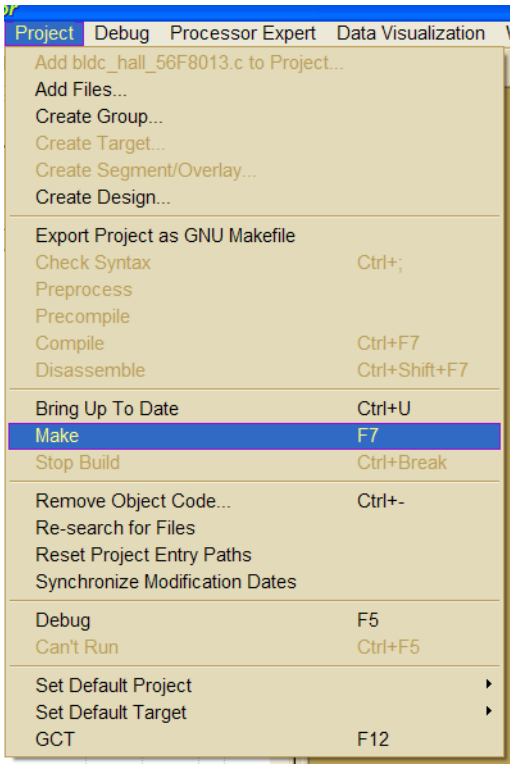


Figure 6-4. Execute *Make* Command

To execute the 3-Phase BLDC drive using variable DC link six-step inverter application, select *Project\Debug* in the CodeWarrior IDE, followed by the *Run* command. For more help with these commands, refer to the CodeWarrior tutorial documentation in the following file located in the CodeWarrior installation folder:

<...>\Help\PDF\Targeting_DSP56800.pdf

CodeWarrior will automatically program the internal Flash of the controller with the executable generated during *Build*. Once the Flash is programmed with the executable code, the parallel cable can be disconnected and the software remains in the Flash after a power-down or reset.

Once the application is running, connect the serial cable and run the FreeMASTER software on your PC to control the application.

Appendix A
References

The following documents can be found on the Freescale web site: http://www.freescale.com.

1. *MC56F8013 Controller Board User's Manual*, Freescale Semiconductor
2. *3-Phase Power Stage with DC/DC Inverter Lite User's Manual*, TPPSDDILUM, Freescale Semiconductor
3. *56F8013 Data Sheet*, MC56F8013, Freescale Semiconductor
4. *CodeWarrior™ Development Studio for Freescale™ DSP56800/E Digital Signal Controllers*, Metrowerks
5. *FreeMASTER for Embedded Applications*, Freescale Semiconductor
6. *DSP56800E_Quick_Start User's Manual*, Freescale Semiconductor
7. *56F83xx Motor Control Library Reference Manual*, Freescale Semiconductor

Appendix B
Glossary

AC — alternating current

ADC — analog-to-digital converter

brush — a component transferring electrical power, from non-rotational terminals mounted on the stator, to the rotor

BLDC — brushless direct current motor

commutator — A mechanical device alternating DC current in a DC commutator motor and providing rotation of DC commutator motor

COP — computer operating properly (watchdog timer

DC — direct current

DC/DC or variable DC link six-step Inverter— power electronics module that converts DC voltage level to a different DC voltage level

DSC — digital signal controller

MC56F80x — a Freescale family of 16-bit DSPs dedicated to motor control

DT — dead time: a short time that must be inserted between the turning off of one transistor in the inverter half bridge and turning on of the complementary transistor due to the limited switching speed of the transistors

duty cycle — the ratio of the amount of time the signal is on to the time it is off. Duty cycle is usually quoted as a percentage

GPIO — general purpose input/output

Hall sensor — a position sensor giving six defined events (each 60 electrical degrees) per electrical revolution (for a 3-phase motor)

interrupt — a temporary break in the sequential execution of a program to respond to signals from peripheral devices by executing a subroutine

I/O — input/output interfaces between a computer system and the external world. A CPU reads an input to sense the level of an external signal and writes to an output to change the level of an external signal

JTAG — Joint Test Action Group: acronym commonly used to refer to an interface allowing on-chip emulation and programming

LED — light emitting diode

PI controller — proportional-integral controller

PLL — phase-locked loop: a clock generator circuit in which a voltage controlled oscillator produces an oscillation that is synchronized to a reference signal

PWM — pulse width modulation

Quad timer — a module with four 16-bit timers

reset — to force a device to a known condition

RPM — revolutions per minute

SCI — serial communication interface module: a module that supports asynchronous communication

software — instructions and data that control the operation of a microcontroller

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